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LANCE TECHNICAL IMPROVEMENT PROGRAM.(U)
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(6) LANCE TECHNICAL IMPROVEMENT PROGRAM

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SUMMARY

The Lance TIP program was initiated as a prequalification evaluation of the Sundstrand accelerometer to determine its availability as a second source to the MIS 13227C requirement for the Lance missile.

Improvements in the Sundstrand accelerometer design, incorporating the basic Q-Flex sensor were required in several areas to establish a low cost, dependable volume production capability for the Lance application. The specific areas of design requiring improvement related, for the most part, exclusively to the Lance application and therefore were funded by the TIP program, since they would not have necessarily occurred during normal Sundstrand Data Control development of the Q-Flex. (cont on p 23)

The specific design tasks derived from the previous 1971 Lance Q-Flex program which yielded sufficient data and experience with the Lance requirements to indicate what items required improvement to qualify the Sundstrand Data Control accelerometer design for Lance.

The TIP program has been finished with complete success in all the specific task areas.

The program did uncover some problems in the electronics design which had not been anticipated. These problems have been corrected. Testing has also demonstrated along with analysis of tolerances and tooling that a modification will not be required to have a high production yield to the spin sensitivity requirement. The analysis and tooling modification study were undertaken as part of the formal qualification program.

With the exception of the marginal spin sensitivity all other performance parameters on the three units built and tested were

well inside the Lance error limits, typically by factors of more than 2 to 1.

The testing included design verification testing in addition to pre environmental exposure and post environmental exposure ATP's. The data and data summaries are contained in this report.

PREFACE

The TIP program units built for design verification testing will have Q-Flex sensors identical to the sensors fabricated under the MM and T Project No. 3773183, for improvement of Quartz Flexure Accelerometer technology. A total of twenty sensors were built of the MM and T configuration. Three sensors were selected for this TIP program from the total of twenty sensors, per a performance evaluation testing selection/screening process, similar to that which will occur for Lance production. The sensors were installed and calibrated in the accelerometer assemblies per a normal production calibration procedure.

The sensor characteristics were very stable; no recalibration was required due to sensor characteristic instability as occurred in the previous Lance program a number of years ago. Indeed, all data indicates that the MM and T and TIP programs have solved the problems which had prevented the Q-Flex from previously being qualified for Lance.

INTRODUCTION

The previous Lance Q-Flex program incorporated a Q-Flex sensor specially modified for the Lance high level acceleration linearity requirements. One of the basic objectives of the TIP program was to modify the electronics to allow use of a standard production Q-Flex sensor with a single minor additional requirement of matching sensor magnets.

The use of a standard production configuration was required to keep the cost of meeting the Lance performance requirements down to an acceptable level. By drawing the sensors for Lance from the normal production run of several hundred sensors, units with very good bias and linearity characteristics can be selected, while those units not meeting Lance requirements can be used for other programs with less stringent bias requirements.

To yield the quantity of sensors anticipated for Lance production, the Q-Flex production run must then, of course, have an acceptably high yield of units which meet the Lance performance requirements. The TIP program included evaluation of an alternate bobbin material and of welded pickoff and torquer flex leads design as bias yield improvement options. Additionally, the MM and T program mentioned in the Preface, had a primary objective of improving the bias stability in the production process.

This report documents the analysis, design modifications, and testing of the Lance units built for the TIP program. The Q-Flex sensors used in the Lance accelerometers, were of the same configuration as the MM and T sensors. The modifications used in these sensors will be qualified for standard Q-Flex production in the near future to make possible a cost effective/reliable quantity Lance production.

MAGNET MATCHING

The first design analysis task in the TIP statement of work was the study of matching magnets for the dual voice coil type design, used in the Q-Flex sensor, to reduce second order nonlinearity.

The Q-Flex sensor is designed to minimize the error produced by the rebalance current in the torque coil. This is accomplished by the incorporation of two opposing voice coil type magnetic circuits. Both circuits produce a radial magnetic field of the same polarity. The magnets in the two circuits are polarized in opposite directions, however, so that the magnetic field produced by the current in the coils adds to the magnetizing potential of one magnet and subtracts from the magnetizing potential of the other magnet. If the two magnets were perfectly matched in minor loop slope, there would be no net change in the magnet field seen by the torque coils. The current scale factor would, therefore, not change with changing "g" levels to produce a nonlinearity type error.

The degree of sensitivity to magnet matching is determined primarily by the efficiency of the magnetic circuit design. In the previous Lance program, a special sensor with a more efficient and more costly magnetic circuit was used, and magnet matching was not required. To reduce cost and insure yield, the standard production sensor is now being used for Lance with the added requirement of matching magnets to reduce nonlinearity.

The matching was accomplished using data from serialized magnetization curves supplied by the magnet vendor on all magnets for standard production Q-Flex sensors. Figure 1 shows a typical magnet demagnetization curve as provided by the magnet vendor.

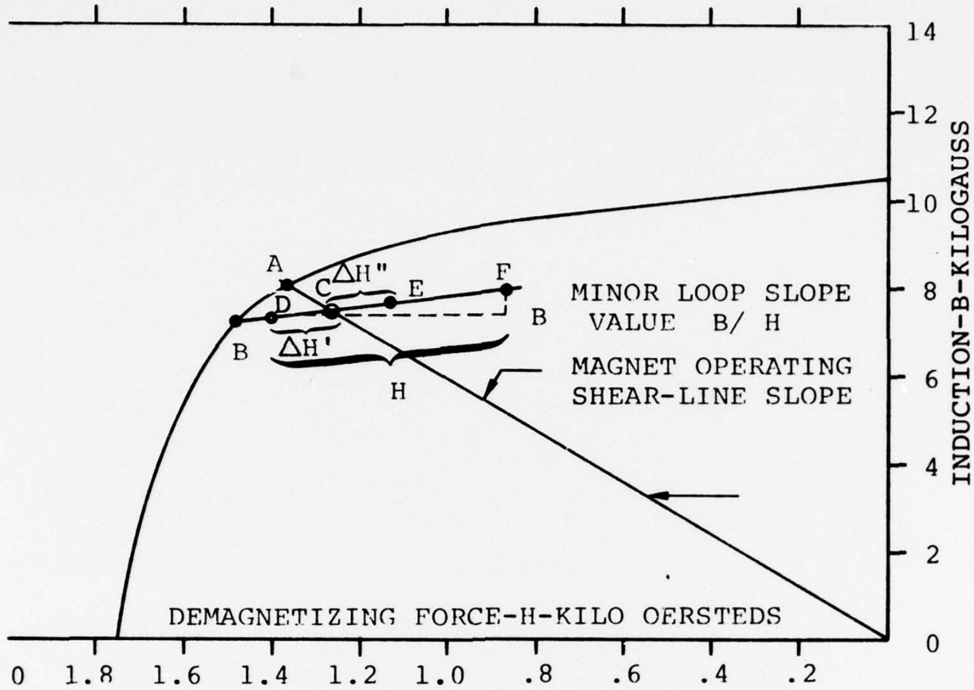

Figure 1 - TYPICAL MAGNET DEMAGNETIZATION CURVE

The primary matching criteria is the minor loop slope. Referring to the figure, the minor loop slope is defined as $\Delta B/\Delta H$ starting from some point D on the linear portion of the minor loop. There is actually a small loop formed, moving back and forth along the minor loop, which is not shown in the figure and the effect of which is not significant for Lance.

When the magnet is initially installed and fully charged in the magnetic circuit, the operating point is point A. Point A is determined by the operating shear line which is a function of magnetic circuit geometry. The magnet is degaussed to point B and recoils to point C when the degaussing field is removed. The degaussing is necessary to insure operation on a linear portion of a minor loop.

The error cancelling operation of the dual opposed matched magnets can best be visualized assuming both magnets are operating at the same point C with the same minor loop slope.

The current in one coil produces a $\Delta H'$ moving one magnet operation to point D; the other coils field $\Delta H''$ moves the other magnets operation to point E. Since both magnets are operating on the same minor loop slope and since $\Delta H'$ equals $\Delta H''$, then the net B in the circuit is unchanged. There would, therefore, be no change in scale factor, as a function of torque coil current, from magnetic interaction and no nonlinearity error from this source.

The minor loop slopes are, of course, not exactly the same. Simple calculations based upon well known electromagnetic forcer equations were performed for the standard production Q-Flex sensor design. These calculations show that a slope matching of 0.03 Gauss per Oersted will produce a second order nonlinearity term of $4\mu g/g^2$ maximum. This nonlinearity level is adequate for Lance and within the resolution and accuracy of the data supplied by the magnet vendor. The minor loop slope can thus be determined adequately by graphical means directly form the curve supplied on each magnet by the vendor.

A second matching criteria of operating point was also used. Matching operating points, flux density, B, in the magnets, is not required for the linearity specification for Lance, but was done to insure a minimum vibration rectification coefficient which is one parameter in the error budget.

The matching criteria is simple enough so that matching could be accomplished by a computer program in quantity production.

NEGATIVE TEMPERATURE COEFFICIENT RESISTOR

The second design analysis task was to design and evaluate a Negative Temperature Coefficient Resistor (NTCR) for use in the load resistor circuit (output current to voltage conversion) to reduce nonlinearity due to sensor self heating.

The concept was to rescale the basic Sundstrand Data Control NTCR for use in a load circuit producing the Lance Specification of 0.5V/g from the standard production Q-Flex nominal 1.3 ma/g.

The NTCR is mounted on the sensor in intimate contact with a surface close to one of the magnets. As the sensor heats up, due to I^2R power dissipation in the torque coil, the current scale factor increases. This increase in current scale factor (CSF) is caused by a decrease in magnet strength as temperature increases. Therefore, to compensate for this effect, the increased temperature of the magnet in the sensor is sensed by the NTCR which decreases in resistance due to its negative temperature coefficient. The temperature coefficient of the NTCR is greater than the CSF temperature coefficient, and the NTCR is, therefore, shunted by a resistor to adjust the total load resistance network temperature coefficient to be precisely the opposite of the CSF temperature coefficient.

The large temperature coefficient of the NTCR also allows its resistance to be made small to reduce I^2R heating in the NTCR itself.

The net result is that the output voltage produced by the sensor current in the NTCR load network is very stable over temperature; therefore, as the sensor heats up due to internal power dissipation in the torque coils at high g levels, the voltage scale factor does not change to produce a nonlinearity error.

Tests were run in the design phase to determine the temperature tracking between the magnet and the NTCR mounted on the magnet return path. The tests showed tracking to better than 1°F, demon-

strating that no significant error in output would occur during transient temperature conditions.

A warmup output drift test was also run to verify that self heating in the NTCR would be negligible. The tests showed the scale factor to be stable within the 3 minute warmup time allowed. Ref. Figure 2.

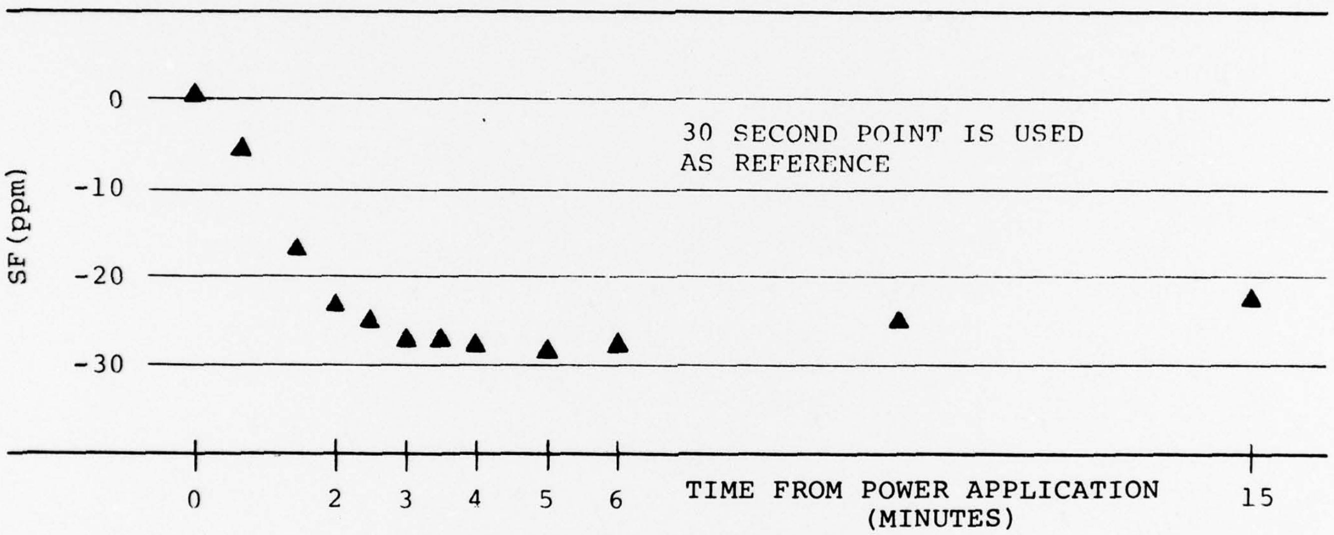

Figure 2 - LANCE SCALE FACTOR WARM-UP

Although testing of linearity with an NTCR prior to the TIP program had shown improved linearity at room ambient temperature, the configuration of the NTCR load network for linearity improvement at the temperature extremes had to be confirmed. Since the I^2R heating in the sensor torque coil is a function of the copper wire resistance, the sensor self heating rate changes with ambient temperature. Additionally, the high NTCR temperature coefficient causes the ratio of its resistance to total load circuit resistance to change with temperature, causing a network temperature

coefficient to CSF temperature coefficient mismatch to a small degree at the temperature extremes.

The testing confirmed that these effects were small relative to the specification requirements. Ref. Figures 6, 7, and 8, which show nonlinearity at the temperature extremes as well as room ambient temperature, on the final configuration units, to be well within the Lance Specification limits.

SERVO LOOP

The third design analysis task was to reconfigure the Lance servo electronics for use with the standard production configuration Q-Flex sensor.

The Q-Flex sensor uses air damping as one servo damping source. The standard production sensor has had a modification incorporated to eliminate errors due to static electricity. This modification reduced the air damping, necessitating a modification of the Lance electronics, originally configured for a special sensor for Lance which had the higher air damping.

The original intent was to use the Dash 3 electronics as presented to the Army in December of 1972 with only minor modifications. The Dash 3 was designed to replace the Dash 2 electronics which had demonstrated marginal reliability during the previous Lance program.

When the program was defined, it was believed by Sundstrand Data Control that only the modification to the servo electronics to account for the lower gas damping factor was required to use the dash 3 electronics; however, when Sundstrand Data Control investigated the availability of the dash 3 design ULS2139G Operational Amplifier, it was discovered that it was not available as a high reliability part as now required for Lance. It was also found that the ULS2139G was not available in a flat pack configuration required by the internal

accelerometer space limitations. The part could not be obtained, and burned-in. Sundstrand Data Control was left with no option except to select a different Op Amp.

A review was made of currently available wide band amplifiers for performance, availability in a high reliability configuration, and multiple sourcing. The wide bandwidth eliminates preselection as was required with the ULS2139 amplifier. Availability in a high reliability configuration eliminates the need for burn-in with its attendant potential problems on a complex part such as a high performance Op Amp. Selecting a part with multiple sources insures availability in future production.

The Op Amp selected was the LM-118F/883B, which being internally compensated for stability, was expected to reduce parts count. The LM-118 does, however, draw more current than the ULS2139 did. Since the total circuit current usage was already at the specification limit, some circuit redesign was required to reduce current drain in the rest of the circuit. Both the regulator and pickoff oscillator sections were modified to reduce current drain.

The breadboard testing of the Dash 3 electronics also disclosed a potential reliability problem which required additional unforeseen circuit modifications. The breadboard testing also disclosed the requirement to add bypass capcitors to the power lines at the LM118's and also to keep the external Op Amp compensation components.

The lack of availability of a number of other components to the high reliability requirement also resulted in additional circuit modifications.

As previously stated, the Lance internal space limitations are a design constraint. The component density on the printed circuit boards is quite high. The circuit modifications resulted, therefore, in a major re-layout of the printed circuit boards.

The new Dash 4 electronics design is more producible, more reliable, and easier to calibrate. Although the changes required by the unforeseen problems increased the cost of the program, the additional effort was well spent.

BOBBIN MATERIAL

The fourth design analysis task was the evaluation of Quartz as a torque coil bobbin material.

There are two torque coil bobbins in the Q-Flex sensor which are attached to the Quartz reed with an adhesive. Any stress on the Quartz reed will warp the reed and produce a bias error through the action of the servo electronics. The attachment of the bobbins produces stress in the Quartz reed through differential expansion thus producing bias errors.

The standard bobbin is made of aluminum which has a relatively high temperature coefficient of expansion as compared to Quartz which has an extremely low temperature coefficient of expansion. As the temperature is changed, the aluminum expands or contracts more than the Quartz of the reed, producing a stress at the interface in the adhesive. The stress in the adhesive is transferred to the Quartz, producing a bias error. As the temperature changes, the bias error changes.

If the adhesive yields with time and/or temperature, a bias instability can result. Fabricating the bobbin from a low temperature coefficeint of expansion material--ideally Quartz--would reduce and/or balance the stress in the adhesive, decreasing possible bias instability.

Sundstrand Data Control fabricated a simplified shape bobbin in a tubular form using chemical milling. Such a form is suitable for testing only and not for production. Bobbins were also fabricated

of Quartz by a vendor using an ultrasonic machining process. The fabrication proved to be very difficult due to breakage caused by the thin wall sections of the bobbin. Such wall thickness, .005 inches, are typical of instrument transducer bobbins.

Three bobbins were successfully fabricated and assembled onto reeds. In the normal Q-Flex there is a bobbin on each side of the reed. To maximize the bias errors introduced by the thermally induced stress in the reed, however, single bobbin reed test assemblies were constructed. With single bobbins, there is no partial cancellation of the stress by a similar stress on the opposite side of the reed. For comparison, assemblies using single Aluminum bobbins were also built.

The assemblies were tested over temperature for bias temperature coefficient (BTC) and bias thermal hysteresis (BTH). The data is summarized in Figure 3. The data indicates no significant improvement in BTH with a possible improvement in BTC.

	ALUMINUM BOBBIN (SINGLE)	QUARTZ BOBBIN (SINGLE)	ALUMINUM BOBBIN (SINGLE)	QUARTZ BOBBIN (SINGLE)
	/BTC/ $\mu G/^{o}F$	/BTC/ $\mu G/^{o}F$	BTH (μ G)	BTH (μ G)
AVG	24.9	7.4	194	165
σ	3.3	4.3	47	146
ABS AVG	--	--	194	165
SAMPLE SIZE	2	3	2	3

Figure 3 - QUARTZ BOBBIN TEST RESULTS BIAS TEMPERATURE COEFFICIENT AND BIAS THERMAL HYSTERESIS

A decision was made not to continue Quartz bobbin development in light of the fabrication problems and the test data showing no definite performance improvement. Recent developments funded by Sundstrand Data Control allowed performance requirements to be met without the added cost and development risk associated with Quartz bobbins.

WELDED PICKOFF AND TORQUER LEADS

The last design analysis task was the evaluation of welded torquer and pickoff leads.

The Q-Flex sensors have gold traces deposited on the reed. The traces extend across the flexures to make electrical contact to the torque coils and capacitive pickoff area.

Connections are made from the traces to the terminal pins of the sensor assembly by gold flex-leads. Connections are also required on the proof mass (paddle) portion of the reed between the copper wires from the two torque coils to put them in series with each other and from the other two torque coil wires to the traces leading across the flexures.

The Q-Flex sensors used for the previous Lance program had all these described connections made with electrically conductive epoxy. The differential expansion, for changes in temperature from the epoxy cure temperature, between the conductive epoxy and the quartz reed substrate, produced stress in the reed resulting in output bias errors. The induced bias errors were not stable as a function of time and temperature.

Since the previous Lance program, Sundstrand Data Control has developed techniques to weld all the subject connections. The stress created by the welding is lower and more stable than that induced by the conductive epoxy.

The connections to the terminal pins are made by a relatively low temperature welding process on both ends of the gold flex leads. The process is called Thermocompression bonding. Special proprietary techniques have been developed by Sundstrand Data Control to thermocompression bond to the gold layer on the quartz. A special technique was required because the gold layer is only hundreds of angstroms in thickness.

A similar Sundstrand Data Control development program was undertaken to replace the conductive epoxy connections of the torque coil wires. A parallel gap welding process was developed for these connections.

Both processes are now used in all standard production Q-Flex sensors and were used in the TIP sensors. The analysis of the bias data is summarized in Figure 4 and clearly shows the improvements obtained. All future Lance units will have all reed electrical connections welded.

DESIGN CHARACTERISTIC	ENDEVCO DESIGN	AFTER T.C. WIRE BONDING FLEX LEADS	AFTER WELDED TORQUER LEADS
TIME FRAME	1971-74	1975	1976-77
BIAS (MG)	4	1	1.0
BTC ($\mu G/^{O}F$)	24	10	8.5
BTH (μG)	150	100	72

Figure 4 - <u>WELDED LEADS BIAS PERFORMANCE</u>

SPIN SENSITIVITY

Spin sensitivity was the only parameter near the Lance specification limit and is discussed briefly herein, therefore, although it was not specifically addressed by the TIP program.

An analysis was performed for Vought Corporation as part of the formal qualification program resulting from the success of the TIP program.

The analysis included calculations to determine the magnitudes to be expected from various possible sources and also included testing of more than 100 units.

The analysis showed that the magnitudes experienced were essentially what would be expected based upon the part and assembly tooling tolerances. The analysis and test data on the 100 units showed that the yield in quantity production would be very high for this parameter no part, assembly, or tooling changes are required.

FABRICATION

Four accelerometer assemblies were assembled and calibrated. All four met all specification requirements easily, with the exception of spin sensitivity on one unit. Spin sensitivity was not tested on the sensor level as will be done in production before installation and calibration in the final assembly.

Only three (3) accelerometers were charged to the TIP program. The fourth accelerometer, with high spin sensitivity, was charged to Sundstrand Data Control and remains Sundstrand Data Control property for future reference testing.

TEST

All three (3) TIP accelerometers were subjected to the testing specified in the SOW which consisted of:

(1) Pre-environmental acceptance tests.

(2) High "g" linearity testing from -40°F to +200°F.

(3) 27 temperature cycles from -65°F to +165°F.

(4) Non-operating vibration per the Storage and Transportation test requirements of the Lance specification.

(5) Post-environmental ATP.

Data from all tests showed all three units well within the Lance specification limits with the exception of spin sensitivity as previously discussed.

Figure 5 shows in tabular form the data from the pre-environmental and post-environmental ATP's.

Figures 6, 7, and 8 show the linearity at ambient temperature and at the temperature extremes.

Figure 9 is a table showing the bias stability thru all environments and including both ATP's.

Figure 10 is a plot of bias through the entire test sequence. This figure shows that the bias stability, which was the main problem during the previous program, is now excellent and well within Lance specification limits.

• BEFORE ENVIRONMENTAL TESTS

UNIT	SF AND B RELATED VALUES				ALIGNMENT		LINEARITY				VIBRATION			SPIN TESTS		LEAK	RSS ERROR	
							HIGH G (%)		IG (MG)		VRC (MG/G^2)							
S/N	SF (V/G)	BIAS (MG)	SFTC (%/°F)	BTC (MG/°F)	VM (MR)	HM (MR)	17-26 AVG	33	30°	60°	5.3G	1.3G	ΔSF (%)	SENS. (MG/RPS^2)	ECM (IN)	RATE (CC/SEC)	BOOST	SUST.
01	0.49996	-0.037	0.0002	0.0015	0.064	-0.015	0.001	.002	-0.002	-0.004	-0.001	0.006	0.002	-0.020	0.021	$<2X10^{-6}$	0.012	0.229
02	0.49997	-0.045	0.0002	0.0004	-0.049	-0.030	0.009	0.012	-0.008	-0.002	-0.002	-0.001	0.001	0.034	0.022	$<2X10^{-6}$	0.024	0.374
03	0.49997	-0.012	0.0003	0.0006	-0.013	0.010	0.004	0.003	-0.003	-0.001	0.001	0.009	0.000	0.025	0.013	$<2X10^{-6}$	0.008	0.274
PEC MIT	.50000 ±.00125	.200 ABS	.0100	.0060	.500	1.50	.020	.030	.200	.200	.160	.160	.026	.044	.050	$2X10^{-6}$	.038	.380

• AFTER ENVIRONMENTAL TESTS

UNIT	SF AND B RELATED VALUES				ALIGNMENT		LINEARITY				VIBRATION			SPIN TESTS		LEAK	RSS ERROR	
							HIGH G (%)		IG (MG)		VRC (MG/G^2)							
S/N	SF (V/G)	BIAS (MG)	SFTC (%/°F)	BTC (MG/°F)	VM (MR)	HM (MR)	17-26 AVG	33	30°	60°	5.3G	1.3G	ΔSF (%)	SENS (MG/RPS^2)	ECM (IN)	RATE (CC/SEC)	BOOST	SUST.
01	0.50012	-0.001	0.0002	0.0015	0.022	0.009	0.001	0.001	-0.007	-0.003	-0.001	0.005	0.003	-0.019	0.029	$<2X10^{-6}$	0.010	0.216
02	0.50013	-0.042	0.0002	0.0004	-0.080	0.080	0.006	0.010	-0.013	-0.099	-0.001	0.006	0.002	0.032	0.028	$<2X10^{-6}$	0.012	0.352
03	0.50014	0.006	0.0002	0.0004	0.020	-0.024	0.002	0.002	-0.004	0.002	0.002	0.007	0.003	0.024	0.022	$<2X10^{-6}$	0.007	0.263
PEC MIT	.50000 ±.00125	.200 ABS	.0100	.0060	.500	1.50	.020	.030	.200	.200	.160	.160	.026	.044	.050	$2X10^{-6}$	.038	.330

Figure 5

LANCE ATP DATA SUMMARY

S/N Equivalency: Unit VS S/C Assy

101=AD4 102=BQ9 103=BR2

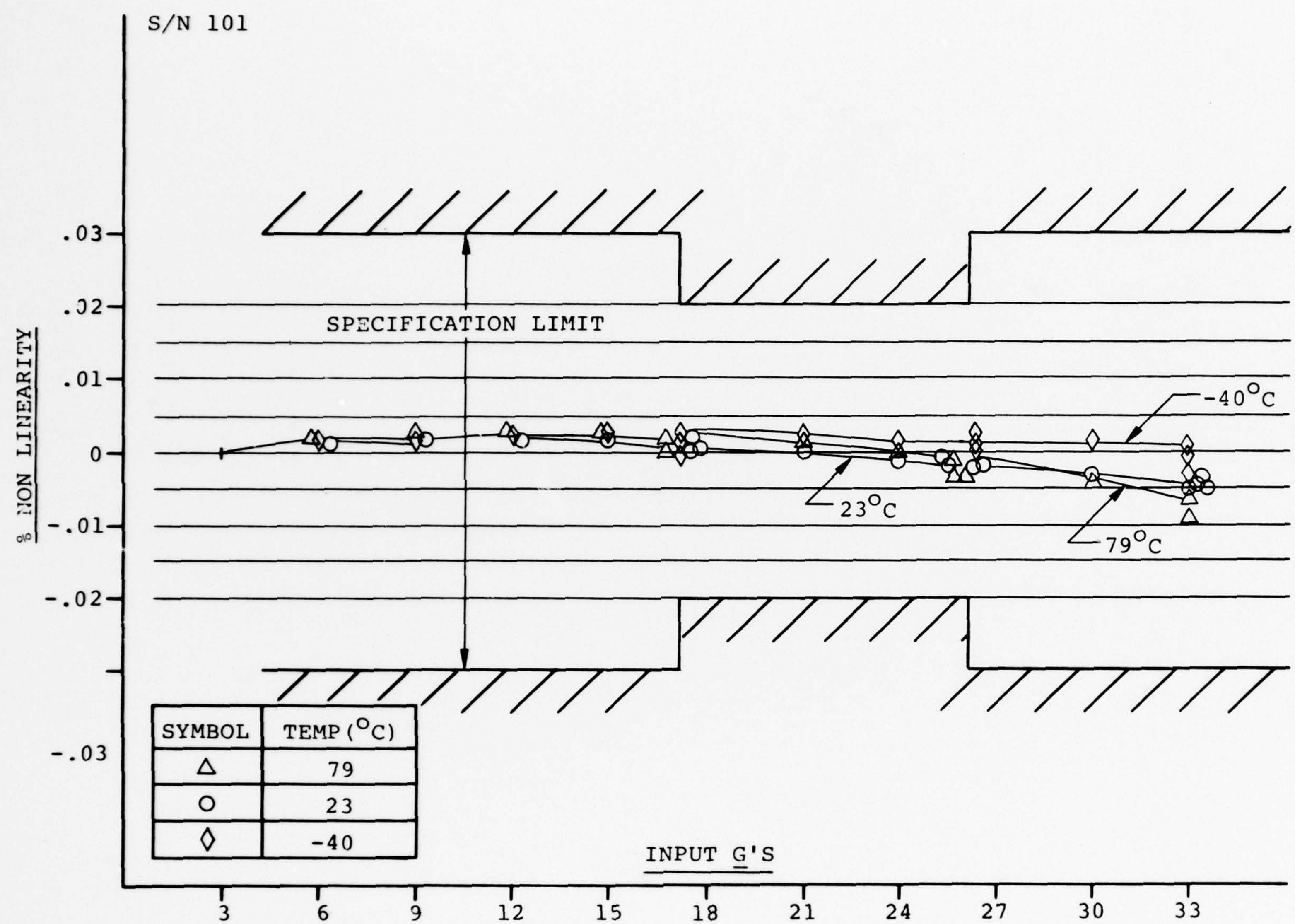

Figure 6

LANCE TIP ACCELEROMETER
DESIGN VERIFICATION TEST
HIGH G LINEARITY

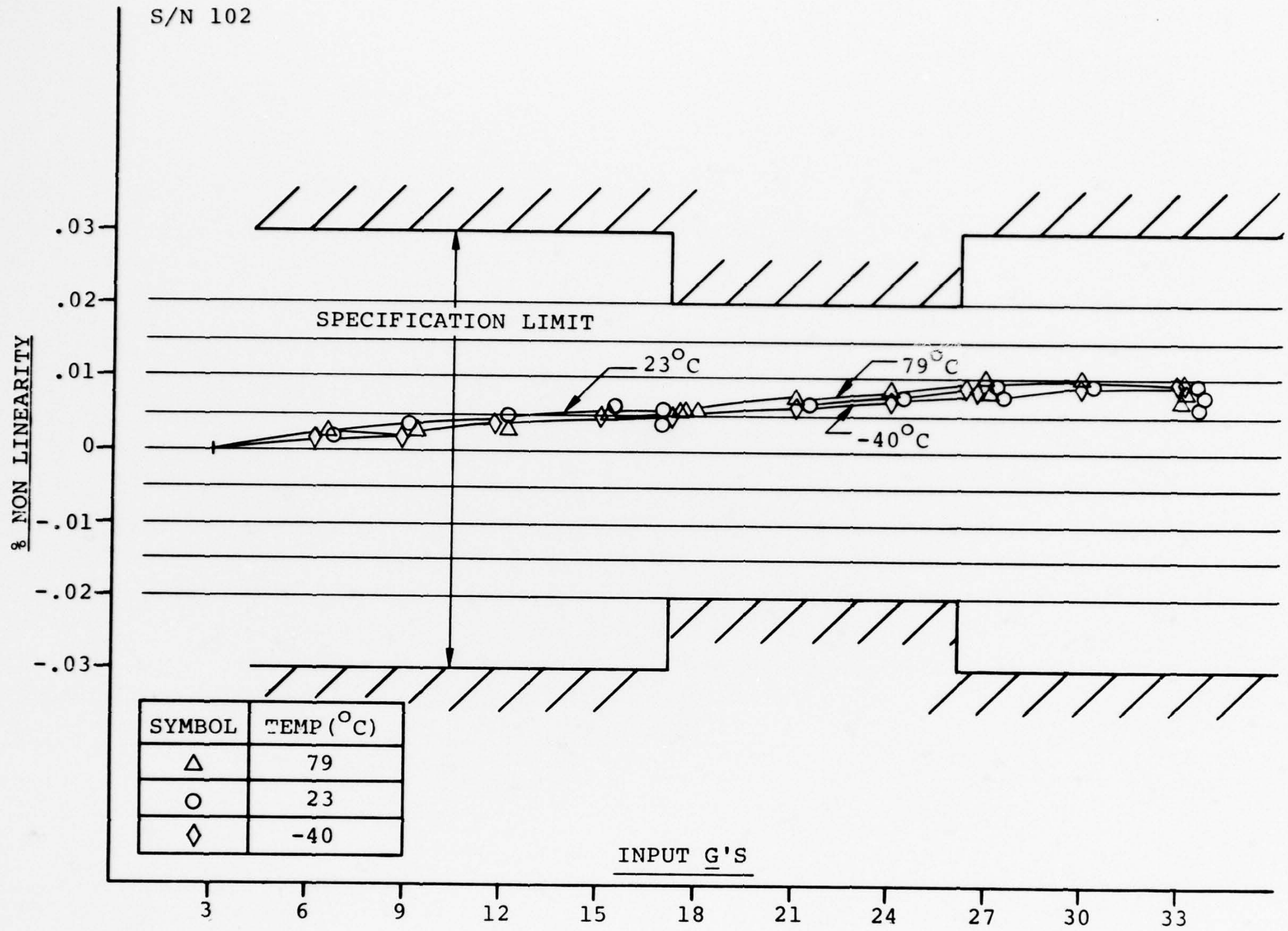

Figure 7

LANCE TIP ACCELEROMETER
DESIGN VERIFICATION TEST
HIGH G LINEARITY

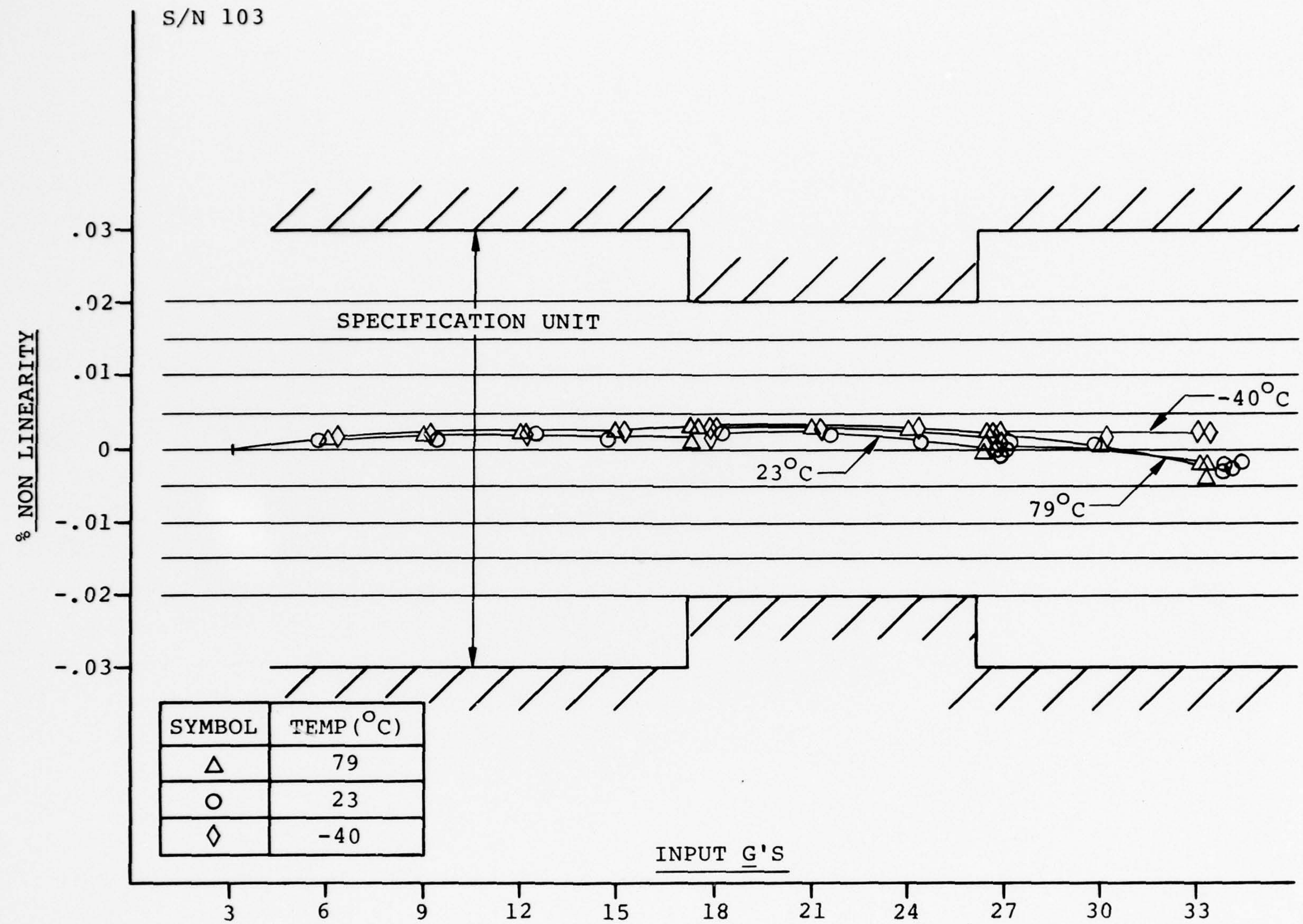

Figure 8

LANCE TIP ACCELEROMETER
DESIGN VERIFICATION TEST
HIGH G LINEARITY

UNIT S/N	INITIAL VALUE	FINAL VALUE	EXTREME VALUES	
			MAX	MIN
101	5	-28	34	-55
102	-23	-48	16	-60
103	24	27	57	-12

Figure 9 LANCE BIAS VALUES

- Distribution Summary
- All values after bias trim
- All environments
- Values in μ G's

RMS BIAS STABILITY MICRO - G'S					
CODE	S/N	ABOUT MEAN	ABOUT INITIAL VALUE	MAX VALUE	MIN VALUE
▲	101	20	21	34	-55
●	102	22	22	16	-60
■	103	18	18	57	-12

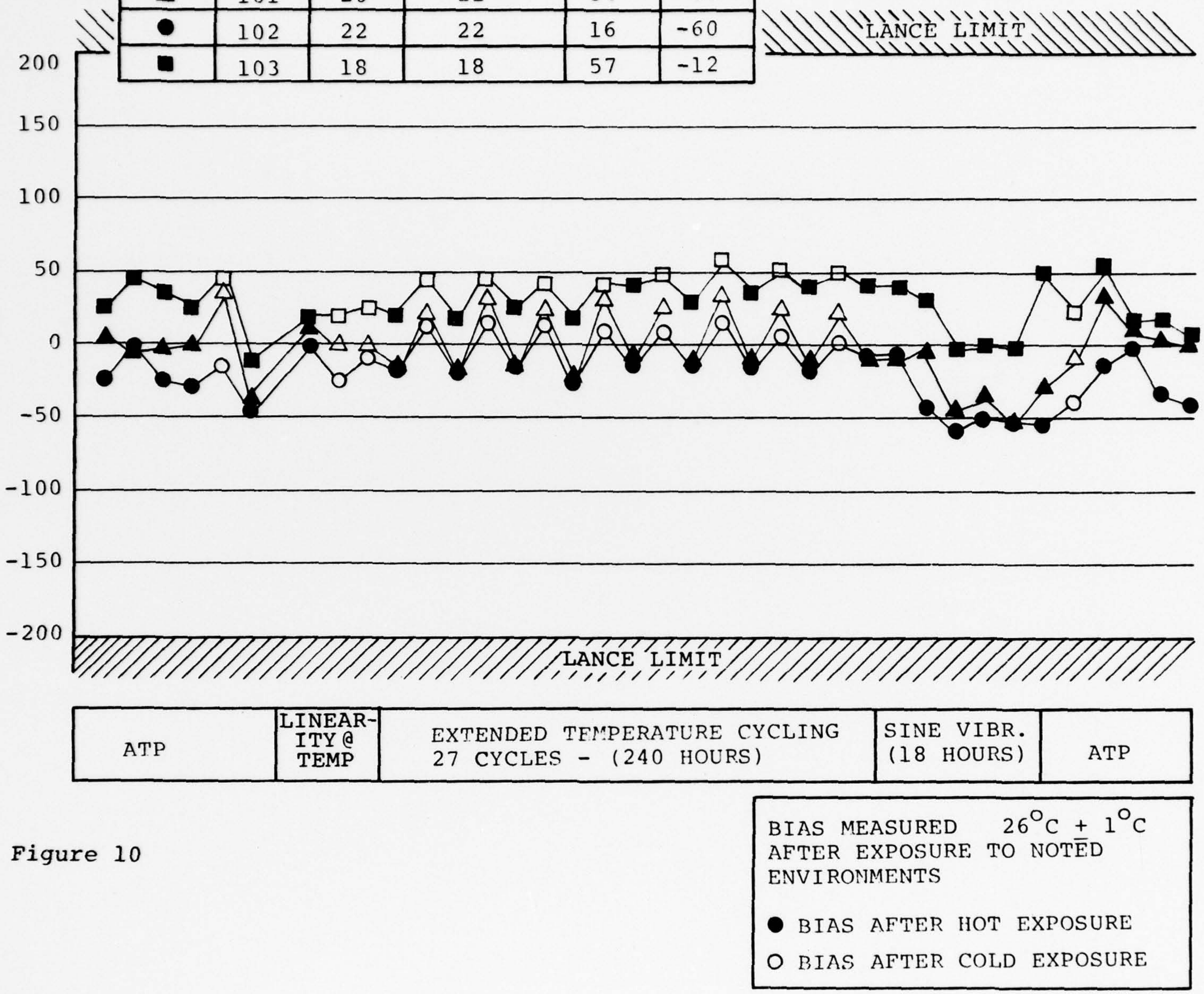

Figure 10

cont fr p 1

CONCLUSIONS

It is concluded that the

The Lance TIP program was completely and extremely successful. Despite the unforseen electronics problems, the hardware was built and formal verification tests were completed on schedule. This success allowed the start of the formal production qualification to make possible timely flight qualification for the Lance missile.